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(54) **CONDUCTIVE SILVER PASTE FOR A METAL-WRAP-THROUGH SILICON SOLAR CELL**

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See application file for complete search history.

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(57) **ABSTRACT**

A conductive silver via paste comprising particulate conductive silver, a vanadium-phosphorus-oxide and an organic vehicle is particularly useful in providing the metallization of the holes in the silicon wafers of MWT solar cells. The result is a metallic electrically conductive via between the collector lines on the front side and the emitter electrode on the back-side of the solar cell. The paste can also be used to form the collector lines on the front-side of the solar cell and the emitter electrode on the back-side of the solar cell. Also disclosed are metal-wrap-through silicon solar cells comprising the fired conductive silver paste.

**19 Claims, No Drawings**

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# CONDUCTIVE SILVER PASTE FOR A METAL-WRAP-THROUGH SILICON SOLAR CELL

## FIELD OF THE INVENTION

This invention is directed to a conductive silver paste for use in a metal-wrap-through (MWT) silicon solar cell and to the respective MWT silicon solar cells made with the conductive silver paste.

## TECHNICAL BACKGROUND OF THE INVENTION

A conventional solar cell with a p-type (p-doped) silicon base has an n-type (n-doped) emitter in the form of an n-type diffusion layer on its front-side. This conventional silicon solar cell structure uses a negative electrode to contact the front-side, i.e. the sun side, of the cell and a positive electrode on the back-side. It is well known that radiation of an appropriate wavelength falling on a p-n junction of a semiconductor serves as a source of external energy to generate electron-hole pairs. The potential difference that exists at a p-n junction causes holes and electrons to move across the junction in opposite directions, thereby giving rise to flow of an electric current that is capable of delivering power to an external circuit. Most solar cells are in the form of a silicon wafer that has been metallized, i.e., provided with metal electrodes which are electrically conductive. Typically, the front-side metallization is in the form of a so-called H pattern, i.e. in the form of a grid cathode comprising thin parallel finger lines (collector lines) and busbars intersecting the finger lines at right angles, whereas the back-side metallization is an aluminum anode in electric connection with silver or silver/aluminum busbars or tabs. The photoelectric current is collected by means of these two electrodes.

Alternatively, a reverse solar cell structure with an n-type silicon base is also known. This cell has a front p-type silicon surface (front p-type emitter) with a positive electrode on the front-side and a negative electrode to contact the back-side of the cell. Solar cells with n-type silicon bases (n-type silicon solar cells) can in theory produce higher efficiency gains compared to solar cells with p-type silicon bases owing to the reduced recombination velocity of electrons in the n-doped silicon.

As in the case of the conventional silicon solar cells, MWT silicon solar cells can be produced as MWT silicon solar cells having a p-type silicon base or, in the alternative, as MWT silicon solar cells having an n-type silicon base. As in conventional solar cells, the emitter of a MWT solar cell is typically covered with a dielectric passivation layer which serves as an antireflective coating (ARC) layer. However, MWT silicon solar cells have a cell design different than that of the conventional solar cells. The front-side electrodes of conventional solar cells reduce the effective photosensitive area available on the front-side of the solar cell and thereby reduce performance of the solar cell. MWT solar cells have both electrodes on the back-side of the solar cell. This is accomplished by drilling, e.g., with a laser, small holes that form vias between the front-side and the back-side of the cell.

The front-side of the MWT silicon solar cell is provided with a front-side metallization in the form of thin conductive metal collector lines which are arranged in a pattern typical for MWT silicon solar cells, e.g., in a grid- or web-like pattern or as thin parallel finger lines. The collector lines are applied from a conductive metal paste having fire-through capability. After drying, the collector lines are fired through the front-

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side dielectric passivation layer thus making contact with the front surface of the silicon substrate. The term "metal paste having fire-through capability" means a metal paste which etches and penetrates through (fires through) a passivation or ARC layer during firing thus making electrical contact with the surface of the silicon substrate.

The inside of the holes and, if present, the narrow rim around the front-edges of the holes, i.e., the diffusion layer not covered with the dielectric passivation layer, is provided with a metallization either in the form of a conductive metal layer on the sides of the hole or in the form of a conductive metal plug that completely fills the hole with conductive metal. The terminals of the collector lines overlap with the metallizations of the holes and are thus electrically connected therewith. The collector lines are applied from a conductive metal paste having fire-through capability. The metallizations of the holes are typically applied from a conductive metal paste and then fired. The metallizations of the holes serve as emitter contacts and form back-side electrodes connected to the emitter or electrically contact other metal deposits which serve as the back-side electrodes connected to the emitter.

The back-side of a MWT silicon solar cell also has the electrodes directly connected to the silicon base. These electrodes are electrically insulated from the metallizations of the holes and the emitter electrodes. The photoelectric current of the MWT silicon solar cell flows through these two different back-side electrodes, i.e., those connected to the emitter and those connected to the base.

Firing is typically carried out in a belt furnace for a period of several minutes to tens of minutes with the wafer reaching a peak temperature in the range of 550° C. to 900° C.

The efficiency of the MWT solar cells is improved since the emitter electrode is located on the back-side and thereby reduces shadowing of the photosensitive area available on the front-side of the solar cell. In addition the emitter electrodes can be larger in size and thereby reduce ohmic losses and all electrical connections are made on the back-side.

When producing a MWT solar cell there is a need for a conductive paste that results in a metalized hole that: (1) has sufficiently low series resistance between the collector lines and the emitter electrode, (2) has good adhesion to the sides of the hole and to the silicon on the backside of the solar cell and (3) has sufficiently high shunting resistance to prevent deleterious electrical connection between portions of the cell, i.e., the emitter and the base.

## SUMMARY OF THE INVENTION

The present invention relates to conductive silver paste comprising:

- (a) silver;
- (b) a vanadium-phosphorus-oxide comprising 80-94 wt %  $V_2O_5$  and 6-20 wt %  $P_2O_5$ , wherein the wt % are based on the total weight of the vanadium-phosphorus-oxide; and
- (c) an organic vehicle, wherein the silver and the Vanadium-phosphorus-oxide are dispersed in the organic vehicle.

This conductive silver paste is particularly useful in providing the metallization of the holes in the silicon wafers of MWT solar cells. This metallization results in a metallic electrically conductive via between the collector lines on the front side and the emitter electrode on the back-side of the solar cell.

Also provided is a metal-wrap-through silicon solar cell comprising the fired conductive silver paste of the invention.

#### DETAILED DESCRIPTION OF THE INVENTION

The conductive silver via paste of the present invention allows for the production of MWT silicon solar cells with improved performance. The conductive silver paste has good hole filling capability. The result is a metallic electrically conductive via between the collector lines on the front side and the emitter electrode on the back-side of the solar cell. The paste can also be used to form the collector lines on the front-side of the solar cell and the emitter electrode on the back-side of the solar cell.

The conductive silver paste comprises silver, a vanadium-phosphorus-oxide and an organic vehicle.

Each constituent of the conductive silver paste of the present invention is discussed in detail below.

#### Silver

In the present invention, the conductive phase of the paste is silver (Ag). The silver can be in the form of silver metal, alloys of silver, or mixtures thereof. Typically, in a silver powder, the silver particles are in a flake form, a spherical form, a granular form, a crystalline form, other irregular forms and mixtures thereof. The silver can be provided in a colloidal suspension. The silver can also be in the form of silver oxide ( $\text{Ag}_2\text{O}$ ), silver salts such as  $\text{AgCl}$ ,  $\text{AgNO}_3$ ,  $\text{AgOOCCH}_3$  (silver acetate),  $\text{AgOOCF}_3$  (silver trifluoroacetate), silver orthophosphate ( $\text{Ag}_3\text{PO}_4$ ), or mixtures thereof. Other forms of silver compatible with the other thick-film paste components can also be used.

In one embodiment the silver is in the form of spherical silver particles. The powder of spherical silver particles has a relatively narrow particle size distribution. In an embodiment the spherical silver particles have a  $d_{50}$  of from 1.7 to 1.9  $\mu\text{m}$ , wherein the median particle diameter,  $d_{50}$ , is determined by means of laser diffraction. In one such embodiment, the spherical silver particles have a  $d_{10} \geq 1 \mu\text{m}$  and a  $d_{90} \leq 3.8 \mu\text{m}$ . In another embodiment, the silver is in the form of irregular (nodular) silver particles having a  $d_{50}$  of from 5.4 to 11.0  $\mu\text{m}$  and a  $d_{90}$  of 9.6-21.7  $\mu\text{m}$ . The  $d_{10}$ ,  $d_{50}$  and  $d_{90}$  represent the 10th percentile, the median or 50th percentile and the 90th percentile of the particle size distribution, respectively, as measured by volume. That is, the  $d_{50}$  ( $d_{10}$ ,  $d_{90}$ ) is a value on the distribution such that 50% (10%, 90%) of the particles have a volume of this value or less.

The silver may be uncoated or the surface at least partially coated with a surfactant. The surfactant may be selected from, but is not limited to, stearic acid, palmitic acid, lauric acid, oleic acid, capric acid, myristic acid and linolic acid and salts thereof, e.g., ammonium, sodium or potassium salts. In one embodiment the surfactant is diethylene glycol and the particle surfaces are essentially completely coated.

In another embodiment, the silver is in the form of silver flake. In one embodiment, an average particle size of the silver flake is less than 10 microns. In another embodiment, the average particle size is less than 5 microns.

The silver is present in the conductive silver paste in a proportion of 85 to 95 wt %, based on the total weight of the conductive silver paste. In one embodiment, the silver is present in the conductive silver paste in a proportion of 85 to 92 wt %, based on the total weight of the conductive silver paste. In another embodiment, the silver is present in the conductive silver paste in a proportion of 88 to 92 wt %, based on the total weight of the conductive silver paste.

#### Vanadium-Phosphorus-Oxide

In one embodiment, the conductive silver paste comprises vanadium-phosphorus-oxide. In one embodiment, the vanadium-phosphorus-oxide is a glass. In a further embodiment, the vanadium-phosphorus-oxide is crystalline, partially crystalline, amorphous, partially amorphous, or combinations thereof. The V—P-glass comprises  $\text{V}_2\text{O}_5$  and  $\text{P}_2\text{O}_5$  and can be referred to as V—P—O. In an embodiment, the vanadium-phosphorus-oxide consists of only  $\text{V}_2\text{O}_5$  and  $\text{P}_2\text{O}_5$ . In an embodiment, the V—P-oxide includes more than one glass composition. In another embodiment, the V—P-oxide includes a glass composition and an additional composition, such as a crystalline composition. The terms “glass”, “glass composition” or “glass frit” will be used herein to represent any of the above combinations of amorphous and crystalline materials.

The glass compositions described herein may also include additional components as disclosed below.

The vanadium-phosphorus-oxide (V—P—O) may be prepared by mixing  $\text{V}_2\text{O}_5$  and  $\text{P}_2\text{O}_5$  (or other materials that decompose into the desired oxides when heated) using techniques understood by one of ordinary skill in the art. Such preparation techniques may involve heating the mixture in air or an oxygen-containing atmosphere to form a melt, quenching the melt, and grinding, milling, and/or screening the quenched material to provide a powder with the desired particle size. Melting the mixture of vanadium and phosphorus oxides is typically conducted to a peak temperature of 800 to 1200° C. The molten mixture can be quenched, for example, on a stainless steel platen or between counter-rotating stainless steel rollers to form a platelet. The resulting platelet can be milled to form a powder. Typically, the milled powder has a  $d_{50}$  of 0.1 to 4.0 microns. One skilled in the art of producing glass frit may employ alternative synthesis techniques such as but not limited to water quenching, sol-gel, spray pyrolysis, quenching by splat cooling on a metal platen, or others appropriate for making powder forms of glass.

Glass compositions are described herein as including percentages of certain components. Specifically, the percentages are the percentages of the components used in the starting material that was subsequently processed as described herein to form a glass composition. Such nomenclature is conventional to one of skill in the art. In other words, the composition contains certain components, and the percentages of those components are expressed as a percentage of the corresponding oxide form. The components of the glass composition may be supplied by various sources such as oxides, halides, carbonates, nitrates, phosphates, hydroxides, peroxides, halogen compounds and mixtures thereof. Herein, the composition of the vanadium-phosphorus-oxide is given in terms of the equivalent oxides no matter the source of the various components. As recognized by one of ordinary skill in the art in glass chemistry, a certain portion of volatile species may be released during the process of making the glass. An example of a volatile species is oxygen.

In one embodiment, the starting mixture used to make the V—P—O is comprised of (based on the total weight of the V—P—O) 80-94 wt %  $\text{V}_2\text{O}_5$  and 6-20 wt %  $\text{P}_2\text{O}_5$ . In another embodiment, the V—P—O is comprised of (based on the total weight of the V—P—O) 82-88 wt %  $\text{V}_2\text{O}_5$  and 12-18 wt %  $\text{P}_2\text{O}_5$ . In still another embodiment, the V—P—O is comprised of (based on the total weight of the V—P—O) 90-94 wt %  $\text{V}_2\text{O}_5$  and 6-10 wt %  $\text{P}_2\text{O}_5$ .

In a further embodiment, in addition to the above  $\text{V}_2\text{O}_5$  and  $\text{P}_2\text{O}_5$ , the starting mixture used to make the V—P—O may include small amounts of one or more of  $\text{TiO}_2$ ,  $\text{SiO}_2$ ,  $\text{SnO}_2$ , and  $\text{B}_2\text{O}_3$  or other components. In one embodiment, the silver

paste has a V—P—O further comprising 0.1-1 wt % TiO<sub>2</sub> (based on the total weight of the V—P—O).

In one embodiment, the V—P—O may be a homogenous powder. In another embodiment, the V—P—O may be a combination of more than one powder, wherein each powder may separately be a homogenous population. The composition of the overall combination of the two powders is within the ranges described above. Separately, these powders may have different compositions, and may or may not be within the ranges described above; however, the combination of these powders is within the ranges described above.

If starting with a fired glass, one of ordinary skill in the art may calculate the percentages of starting components described herein using methods known to one of skill in the art including, but not limited to: Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS), Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES), and the like. In addition, the following exemplary techniques may be used: X-Ray Fluorescence spectroscopy (XRF); Nuclear Magnetic Resonance spectroscopy (NMR); Electron Paramagnetic Resonance spectroscopy (EPR); Mossbauer spectroscopy; electron microprobe Energy Dispersive Spectroscopy (EDS); electron microprobe Wavelength Dispersive Spectroscopy (WDS); Cathodo-Luminescence (CL).

One of ordinary skill in the art would recognize that the choice of raw materials could unintentionally include impurities that may be incorporated into the glass during processing. For example, the impurities may be present in the range of hundreds to thousands ppm. The presence of the impurities would not alter the properties of the glass, the thick-film composition, or the fired device. For example, a solar cell containing the thick-film composition may have the efficiency described herein, even if the thick-film composition includes impurities.

The V—P—O is present in the conductive silver paste in a proportion of 0.2 to 5.5 wt %, based on the total weight of the conductive silver paste. In one embodiment, the V—P—O is present in the conductive silver paste in a proportion of 0.5 to 2 wt %, based on the total weight of the conductive silver paste. In another embodiment, the V—P—O is present in the conductive silver paste in a proportion of 4 to 5 wt %, based on the total weight of the conductive silver paste.

The vanadium-phosphorus-oxide (V—P—O) composition can be prepared by mixing and blending V<sub>2</sub>O<sub>5</sub> and P<sub>2</sub>O<sub>5</sub> powders, and optionally, other components. The blended powder batch materials are loaded into a platinum alloy crucible and then inserted into a furnace at 900-1000° C. using an air or O<sub>2</sub>-containing atmosphere. The duration of the heat treatment is 20 minutes following the attainment of a full solution of the constituents. The resulting low viscosity liquid resulting from the fusion of the constituents is then quenched by metal roller. The quenched glass is then milled and screened to provide a powder with a d<sub>50</sub> of 0.1 to 3.0 microns.

One embodiment made by the above process has a composition of 85.37 wt % V<sub>2</sub>O<sub>5</sub> and 14.63 wt % P<sub>2</sub>O<sub>5</sub>. Another embodiment made by the above process has a composition of 81.74 wt % V<sub>2</sub>O<sub>5</sub> and 18.26 wt % P<sub>2</sub>O<sub>5</sub>. Still another embodiment made by the above process has a composition of 92.02 wt % V<sub>2</sub>O<sub>5</sub> and 7.98 wt % P<sub>2</sub>O<sub>5</sub>. These were prepared by mixing and blending the V<sub>2</sub>O<sub>5</sub> and P<sub>2</sub>O<sub>5</sub> powders and processing as described above. Yet another embodiment made by the above process has a composition of 81.30 wt % V<sub>2</sub>O<sub>5</sub>, 18.16 wt % P<sub>2</sub>O<sub>5</sub>, and 0.54 wt % TiO<sub>2</sub>. It was prepared by mixing and blending the V<sub>2</sub>O<sub>5</sub>, P<sub>2</sub>O<sub>5</sub> and TiO<sub>2</sub> powders and processing as described above.

## Sintering Inhibitors

In one embodiment, the conductive silver paste further comprises a sintering inhibitor that is dispersed in the organic vehicle. The sintering inhibitor slows down sintering and is believed to thereby reduce shunting. In one such embodiment, the sintering inhibitor is titanium resinate or any compound that decomposes into titanium resinate at temperatures of 550° C. to 900° C. and mixtures thereof. The titanium resinate is present in the conductive silver paste in a proportion of 0.1 to 1 wt %, based on the total weight of the conductive silver paste. In one embodiment, the titanium resinate is present in the conductive silver paste in a proportion of 0.1 to 0.7 wt %, based on the total weight of the conductive silver paste. In another embodiment, the titanium resinate is present in the conductive silver paste in a proportion of 0.2 to 0.4 wt %, based on the total weight of the conductive silver paste.

In another embodiment, the sintering inhibitor is titanium dioxide. The titanium dioxide is present in the conductive silver paste in a proportion of 0.1 to 1 wt %, based on the total weight of the conductive silver paste.

The conductive silver paste may comprise one or more other inorganic additives.

## Organic Vehicle

The conductive silver paste comprises an organic vehicle. The organic vehicle is an organic solvent or an organic solvent mixture or, in another embodiment, the organic vehicle is a mixture of organic polymer in organic solvent.

A wide variety of inert viscous materials can be used as an organic vehicle. The organic vehicle is one in which the other constituents, i.e., the particulate conductive silver and the V—P—O are dispersible with an adequate degree of stability. The properties, in particular, the rheological properties, of the organic vehicle must be that they lend good application properties to the conductive silver paste composition, including: stable dispersion of insoluble solids, appropriate viscosity and thixotropy for application, appropriate wettability of the paste solids, a good drying rate, and good firing properties.

The organic vehicle is typically a solution of one or more polymers in one or more solvents. The most frequently used polymer for this purpose is ethyl cellulose. Other examples of polymers are ethylhydroxyethyl cellulose, wood rosin, mixtures of ethyl cellulose and phenolic resins, polymethacrylates of lower alcohols, and monobutyl ether of ethylene glycol monoacetate. The most widely used solvents found in thick film compositions are ester alcohols and terpenes such as alpha- or beta-terpineol or mixtures thereof with other solvents such as kerosene, dibutylphthalate, butyl carbitol, butyl carbitol acetate, hexylene glycol and high boiling alcohols and alcohol esters. In addition, volatile liquids for promoting rapid hardening after application on the substrate can be included in the vehicle. Various combinations of these and other solvents are formulated to obtain the viscosity and volatility requirements desired.

The organic vehicle content in the conductive silver paste is dependent on the method of applying the paste and the kind of organic vehicle used. In one embodiment, it is from 5 to 20 wt %, based on the total weight of the conductive silver paste composition. In another embodiment, it is from 9 to 15 wt %, based on the total weight of the conductive silver paste composition. These wt % include the organic solvent, any organic polymer and any other organic additives.

The conductive silver paste may comprise one or more other organic additives, for example, surfactants, thickeners, rheology modifiers and stabilizers. An organic additive may

be part of the organic vehicle. However, it is also possible to add an organic additive separately when preparing the conductive silver paste.

#### Conductive Silver Paste

The application viscosity of the conductive silver paste is in the range of 150 to 300 Pa-s when it is measured at a spindle speed of 10 rpm and 25° C. by a utility cup using a Brookfield HBT viscometer and #14 spindle.

The conductive silver paste is applied to the holes of the silicon wafer to provide metallization and a conducting via from the front-side to the back-side of the metal-wrap-through solar cell, or from the backside to the front side. The conductive silver paste is applied in a way to completely fill the hole with conductive silver or in the form of a layer to cover at least the inside of the holes with a metallization, i.e. to form the metallization of at least the inside of the holes.

The method of conductive silver paste application may be printing, for example, screen printing. The application may be performed from the front-side and/or from the back-side of the solar cell.

After application, the conductive silver paste is dried, for example, for a period of 1 to 10 minutes with the silicon wafer reaching a peak temperature in the range of 100° C. to 300° C. Drying can be carried out making use of, for example, belt, rotary or stationary driers and in particular, IR (infrared) belt driers.

The dried conductive silver paste is fired to form the finished metallization of the holes. These metallization serve as emitter contacts and back-side contacts of the MWT silicon solar cell. The firing is performed for a period of 1 to 5 minutes with the silicon wafer reaching a peak temperature in the range of 550° C. to 900° C. The firing can be carried out making use of single or multi-zone belt furnaces, in particular, multi-zone IR belt furnaces. The firing can take place in an inert gas atmosphere or in the presence of oxygen, e.g., in the presence of air. During firing the organic substance including non-volatile organic material and the organic portion not evaporated during the drying is removed. The organic substance removed during firing includes organic solvent, organic polymer and any organic additives present.

The conductive silver paste firing process can be a co-firing process in which front-side metallization in the form of thin conductive metal collector lines arranged in a pattern typical for MWT silicon solar cells and applied from a conductive metal paste and/or silver backside collector contacts applied from a back-side silver paste are fired at the same time.

The conductive silver paste can be applied to MWT silicon solar cells that have emitters within the vias as well as to MWT silicon solar cells that do not have emitters within the vias. The conductive silver paste can also be applied to MWT silicon solar cells that have antireflective coating within the vias as well as to MWT silicon solar cells that do not have antireflective coating within the vias. The conductive silver paste can be applied to MWT silicon solar cells with n-type or p-type silicon bases.

Also provided is a metal-wrap-through silicon solar cell comprising the fired conductive silver paste of the invention.

## EXAMPLES

### Example 1

#### Vanadium-Phosphorus-Oxide Preparation

A vanadium-phosphorus-oxide (V—P—O) composition was prepared by mixing and blending V<sub>2</sub>O<sub>5</sub> and P<sub>2</sub>O<sub>5</sub> powders to result in a V—P—O composition consisting of 85.37

wt % V<sub>2</sub>O<sub>5</sub> and 14.63 wt % P<sub>2</sub>O<sub>5</sub>. The blended powder batch materials were loaded to a platinum alloy crucible then inserted into a furnace and heated at 900° C. in air or O<sub>2</sub> for one hour to melt the mixture. The liquid melt was quenched from 900° C. by removing the platinum crucible from the furnace and pouring the melt through counter rotating a stainless steel rollers gapped to 0.010-0.020". The resulting material was coarsely crushed in a stainless steel container. The crushed material was then ball-milled in an alumina-silicate ceramic ball mill with zirconia media until the d<sub>50</sub> was 1-4 microns. The ball-milled material was then separated from the milling balls and screened. The dried powder was run through screens with 40, 200, 325 or 500 mesh to provide the V—P—O powder used in the thick film paste preparations described below.

#### Thick Film Paste Composition Preparation

The thick film paste was prepared by mixing Ag, the V—P—O powder prepared above in Example 1, organic medium and titanium resinate. The Ag in the form of irregular (nodular) silver particles having a d<sub>50</sub> of from 5.4 to 11.0 μm. and the V—P—O were added to the organic medium with continued stirring. Since the silver was the major portion of the solids it was added slowly to insure better wetting. The paste was then passed through a three-roll mill at a 1 mil gap several times. The degree of dispersion was measured by fine of grind (FOG) to insure that the FOG was less than or equal to 20/10.

The proportions of ingredients used in this Example were 90.5 wt % Ag, 1.5 wt % V—P—O, 0.2 wt % titanium resinate and 7.8 wt % organic medium, based on the total weight of the four ingredients.

#### Test Electrodes

In order to determine the adhesion properties of electrodes formed from the instant paste composition, the paste composition was screen printed onto a silicon wafer surface in the form of an electrode. The paste was then dried and fired in a furnace. The dried thickness of the sample was 3 μm.

#### Test Procedure-Adhesion

After firing, a solder ribbon was soldered to the fired paste. Since the current invention comprises only Pb-free V—P—O, Pb-free solder was used. The Pb-free solder used was 96.5 Sn/3.5 Ag. Solder temperature for the Pb-free solder was in the range of 345-375° C., solder time was 5-7 s. Flux used was Kesler 9552.

The soldered area was approximately 2 mm×2 mm. The adhesion strength was obtained by pulling the ribbon at an angle of 90° to the surface of the cell. An assessment of the adhesion strength was assigned as low, adequate, or good, based on the assumption that an adhesion strength less than 2 N is considered low; values in the range of 2 N to 3 N is adequate, values in the range of 3 N to 4 N or above is good.

Adhesion was determined for the sample of Example 1 and the measurement was repeated over a hundred times. The average adhesion was 3.97 N.

### Example 2

Example 2 was carried out as described in Example 1 except that the paste was prepared using 90.25 wt % Ag, 1.75 wt % V—P—O, 0.2 wt % titanium resinate and 7.8 wt % organic medium, based on the total weight of the four ingredients.

Adhesion was determined for the sample of Example 2 as described in Example 1. The average adhesion 3.96 N.

### Example 3

Example 3 was carried out as described in Example 1 except that the paste was prepared using 87.5 wt % Ag, 4.5 wt

% V—P—O, 0.2 wt % titanium resinate and 7.8 wt % organic medium, based on the total weight of the four ingredients.

Adhesion was determined for the sample of Example 3 as described in Example 1. The average adhesion was 5.66 N.

What is claimed is:

1. A conductive silver paste comprising:
  - (a) 85-95 wt % silver;
  - (b) 0.2-5.5 wt % vanadium-phosphorus-oxide consisting of 80-94 wt % and 6-20 wt %  $P_2O_5$ , wherein the wt % of the  $V_2O_5$  and  $P_2O_5$  are based on the total weight of said vanadium-phosphorus-oxide; and
  - (c) 5-20 wt % organic vehicle, wherein said silver and said vanadium-phosphorus-oxide are dispersed in said organic vehicle and wherein the wt % of the silver, the vanadium-phosphorus-oxide and the organic vehicle are based on the total weight of the conductive silver paste.
2. The conductive silver paste of claim 1, wherein said silver is in the form of spherical silver particles.
3. The conductive silver paste of claim 2, said spherical silver particles having a  $d_{50}$  of from 1.7 to 1.9  $\mu m$  and a  $d_{10} \geq 1 \mu m$  and a  $d_{90} \leq 3.8 \mu m$ .
4. The conductive silver paste of claim 1, wherein said silver is in the form of irregular particles having a  $d_{50}$  of from 5.4 to 11.0  $\mu m$  and a  $d_{90}$  of from 9.6 to 21.7  $\mu m$ .
5. The conductive silver paste of claim 1, said vanadium-phosphorus-oxide consisting of 82-88 wt %  $V_2O_5$  and 12-18 wt %  $P_2O_5$ , wherein the wt % are based on the total weight of said vanadium-phosphorus-oxide.
6. A metal-wrap-through silicon solar cell with an n-type or a p-type silicon base comprising the fired conductive silver paste of claim 5.
7. The conductive silver paste of claim 1, said vanadium-phosphorus-oxide consisting of 90-94 wt %  $V_2O_5$  and 6-10 wt %  $P_2O_5$ , wherein the wt % are based on the total weight of said vanadium-phosphorus-oxide.
8. A metal-wrap-through silicon solar cell with an n-type or a p-type silicon base comprising the fired conductive silver paste of claim 7.
9. The conductive silver paste of claim 1, said conductive silver paste comprising 85-92 wt % silver and 0.5 to 2 wt % vanadium-phosphorus-oxide, based on the total weight of said conductive silver paste.

10. A metal-wrap-through silicon solar cell with an n-type or a p-type silicon base comprising the fired conductive silver paste of claim 9.

11. The conductive silver paste of claim 1, said conductive silver paste comprising 88-92 wt % silver and 4 to 5 wt % vanadium-phosphorus-oxide, based on the total weight of said conductive silver paste.

12. A metal-wrap-through silicon solar cell with an n-type or a p-type silicon base comprising the fired conductive silver paste of claim 11.

13. The conductive silver paste of claim 1, said conductive silver paste further comprising a sintering inhibitor.

14. The conductive silver paste of claim 1, said conductive silver paste comprising:

0.1 to 1 wt % sintering inhibitor titanium resinate, based on the total weight of the conductive silver paste.

15. The conductive silver paste of claim 1, said conductive silver paste comprising 0.1 to 1 wt % sintering inhibitor titanium dioxide, based on the total weight of the conductive silver paste.

16. A metal-wrap-through silicon solar cell with an n-type or a p-type silicon base comprising the fired conductive silver paste of claim 1.

17. A conductive silver paste further comprising:

(a) 85-95 wt % silver;

(b) 0.2-5.5 wt % vanadium-phosphorus-oxide consisting of 80-94 wt %  $V_2O_5$  6-20 wt %  $P_2O_5$ , and 0.1-1 wt %  $TiO_2$ , wherein the wt % of the  $V_2O_5$ ,  $P_2O_5$  and  $TiO_2$  are based on the total weight of said vanadium-phosphorus-oxide; and

(c) 5-20 wt % organic vehicle, wherein said silver and said vanadium-phosphorus-oxide are dispersed in said organic vehicle and wherein the wt % of the silver, the vanadium-phosphorus-oxide and the organic vehicle are based on the total weight of the conductive silver paste.

18. A metal-wrap-through silicon solar cell with an n-type or a p-type silicon base comprising the fired conductive silver paste of claim 17.

19. The conductive silver paste of claim 17, said conductive silver paste further comprising a sintering inhibitor.

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